CHAPTER 9

STRUCTURAL PROPERTIES

9-1. Introduction. Unlike gravity dams that use the weight of the concrete for stability, arch dams utilize the strength of the concrete to resist the hydrostatic loads. Therefore, the concrete used in arch dams must meet very specific strength requirements. In addition to meeting strength criteria, concrete used in arch dams must meet the usual requirements for durability, permeability, and workability. Like all mass concrete structures, arch dams must keep the heat of hydration to a minimum by reducing the cement content, using low-heat cement, and using pozzolans. This chapter discusses the material investigations and mixture proportioning requirements necessary to assure the concrete used in arch dams will meet each of these special requirements. This chapter also discusses the testing for structural and thermal properties that relates to the design and analysis of arch dams, and it provides recommended values which may be used prior to obtaining test results.

9-2. Material Investigations. General guidance on concrete material investigations can be found in EM 1110-2-2000. The material discussed in the next few paragraphs is intended to supplement EM 1110-2-2000 and to provide specific guidance in the investigations that should be performed for arch dams.

a. Cement. Under normal conditions the cementitious materials used in an arch dam will simply be a Type II portland cement (with heat of hydration limited to 70 cal/gm) in combination with a pozzolan. However, Type II cement may not be available in all project areas. The lack of Type II cement does not imply that massive concrete structures, such as arch dams, are not constructable. It will only be necessary to investigate how the available materials and local conditions can be utilized. For example, the heat of hydration for a Type I cement can be reduced by modifying the cement grinding process to provide a reduced fineness. Most cement manufacturers should be willing to do this since it reduces their cost in grinding the cement. However, there would not necessarily be a cost savings to the Government, since separate silos would be required to store the specially ground cement. In evaluating the cement sources, it is preferable to test each of the available cements at various fineness to determine the heat generation characteristics of each. This information is useful in performing parametric thermal studies.

b. Pozzolans. Pozzolans are siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value; however, pozzolans will chemically react, in finely divided form and in the presence of moisture, with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. There are three classifications for pozzolans: Class N, Class F, and Class C.

(1) Class N pozzolans are naturally occurring pozzolans that must be mined and ground before they can be used. Many natural pozzolans must also be calcined at high temperatures to activate the clay constituent. As a result, Class N pozzolans are not as economical as Classes F and C, if these other classes are readily available.

(2) Classes F and C are fly ashes which result from burning powdered coal in boiler plants, such as electric generating facilities. The ash is collected to prevent it from entering the atmosphere. Being a byproduct of another industry, fly ash is usually much cheaper than cement. However, some of the savings in material may be offset by the additional material handling and storage costs. Fly ash particles are spherical and are about the same fineness as cement. The spherical shape helps reduce the water requirement in the concrete mix.

(3) It is important that the pozzolan source produce consistent material properties, such as constant fineness and constant carbon content. Otherwise, uniformity of concrete will be affected. Therefore, an acceptable pozzolan source must be capable of supplying the total project needs.

(4) In mass concrete, pozzolans are usually used to replace a portion of the cement, not to increase the cementitious material content. This will reduce the amount of portland cement in the mixture proportions. Not only will this cement reduction lower the heat generated within the mass, but the use of pozzolans will improve workability, long-term strength, and resistance to attack by sulphates and other destructive agents. Pozzolans can also reduce bleeding and permeability and control alkali-aggregate reaction.

(5) However, when pozzolans are used as a cement replacement, the time rate of strength gain will be adversely affected; the more pozzolan replacement, the lower the early strength. As a result, an optimization study should be performed to determine the appropriate amount of pozzolan to be used. The optimization study must consider both the long-term and the early-age strengths. The early-age strength is important because of the need for form stripping, setting of subsequent forms, and lift joint preparation. The practical limits on the percentage of pozzolan that should be used in mass concrete range from 15 to 50 percent. During the planning phases and prior to performing the optimization study, a value of 25 to 35 percent can be assumed.

c. Aggregates. Aggregates used in mass concrete will usually consist of natural sand, gravel, and crushed rock. Natural sands and gravels are the most common and are used whenever they are of satisfactory quality and can be obtained economically in sufficient quantity. Crushed rock is widely used for the larger coarse aggregates and occasionally for smaller aggregates including sand when suitable materials from natural deposits are not economically available. However, production of workable concrete from sharp, angular, crushed fragments usually requires more vibration and cement than that of concrete made with well-rounded sand and gravel.

(1) Suitable aggregate should be composed of clean, uncoated, properly shaped particles of strong, durable materials. When incorporated into concrete, it should satisfactorily resist chemical or physical changes such as cracking, swelling, softening, leaching, or chemical alteration. Aggregates should not contain contaminating substances which might contribute to deteriorating or unsightly appearance of the concrete.

(2) The decision to develop an on-site aggregate quarry versus hauling from an existing commercial quarry should be based on an economic feasibility study of each. The study should determine if the commercial source(s) can produce aggregates of the size and in the quantity needed. If an on-site

quarry is selected, then the testing of the on-site source should include a determination of the effort required to produce the aggregate. This information should be included in the contract documents for the prospective bidders.

d. Water. All readily available water sources at the project site should be investigated during the design phase for suitability for mixing and curing water. The purest available water should be used. When a water source is of questionable quality, it should be tested in accordance with CRD-C 400 and CRD-C 406 (USAEWES 1949). When testing the water in accordance with CRD-C 406, the designer may want to consider including ages greater than the 7 and 28 days required in the CRD specification. This is especially true when dealing with a design age of 180 or 360 days, because the detrimental effects of the water may not become apparent until the later ages. Since there are usually differences between inplace concrete using an on-site water source and lab mix designs using ordinary tap water, the designer may want to consider having the lab perform the mix designs using the anticipated on-site water.

e. Admixtures. Admixtures normally used in arch dam construction include air-entraining, water-reducing, retarding, and water-reducing/retarding admixtures. During cold weather, accelerating admixtures are sometimes used. Since each of these admixtures is readily available throughout the United States, no special investigations are required.

9-3. Mix Designs. The mixture proportions to be used in the main body of the dam should be determined by a laboratory utilizing materials that are representative of those to be used on the project. The design mix should be the most economical one that will produce a concrete with the lowest practical slump that can be efficiently consolidated, the largest maximum size aggregate that will minimize the required cementitious materials, adequate early-age and later-age strength, and adequate long-term durability. In addition, the mix design must be consistent with the design requirements discussed in the other chapters of this manual. A mix design study should be performed to include various mixture proportions that would account for changes in material properties that might reasonably be expected to occur during the construction of the project. For example, if special requirements are needed for the cement (such as a reduced fineness), then a mix with the cement normally available should be developed to account for the possibility that the special cement may not always be obtainable. This would provide valuable information during construction that could avoid prolonged delays.

a. Compressive Strength. The required compressive strength of the concrete is determined during the static and dynamic structural analyses. EM 1110-2-2000 requires that the mixture proportions for the concrete be selected so that the average compressive strength (f_{cr}) exceeds the required compressive strength (f'_c) by a specified amount. The amount that f_{cr} should exceed f'_c depends upon the classification of the concrete (structural or nonstructural) and the availability of test records from the concrete production facility. Concrete for an arch dam meets the requirements in EM 1110-2-2000 for both structural concrete and nonstructural (mass) concrete. That is, arch dams rely on the strength of the concrete in lieu of its mass, which would classify it as a structural concrete. However, the concrete is unreinforced mass concrete, which would classify it as a nonstructural concrete. For determining the required compressive strength (f_{cr}) for use in the mix designs, the preferred method would be the method for nonstructural concrete.

Assuming that no test records are available from the concrete plant, this would require the mix design to be based on the following relationship:

$$f_{cr} = f'_c + 600 \text{ psi} \quad (9\text{-}1)$$

This equation will be valid during the design phase, but it can change during construction of the dam as test data from the concrete plant becomes available.

b. Water-cement Ratio. Table 9-1 shows the maximum water-cement ratios recommended for concrete used in most arch dams. These water-cement ratios are based on minimum durability requirements. The strength requirements in the preceding paragraph may dictate an even lower value. In thin structures (thicknesses less than approximately 30 feet) it may not be practical to change mixes within the body of the structure, so the lowest water-cement ratio should be used throughout the dam. In thick dams (thicknesses greater than approximately 50 feet), it may be practical to use an interior class of concrete with a water-cement ratio as high as 0.80. However, the concrete in the upstream and downstream faces should each extend into the dam a minimum of 15 to 20 feet before transitioning to the interior mixture. In addition, the interior concrete mix should meet the same strength requirements of the surface mixes.

TABLE 9-1

Maximum Permissible Water-Cement Ratio

Location in Dam	Severe or Moderate Climate	Mild Climate
Upstream face above minimum pool	0.47	0.57
Interior (for thick dams only)	0.80	0.80
Downstream face and upstream face below minimum pool	0.52	0.57

c. Maximum Size Aggregate. EM 1110-2-2000 recommends 6 inches as the nominal maximum size aggregate (MSA) for use in massive sections of dams. However, a 6-inch MSA may not always produce the most economical mixture proportion. Figure 9-1 shows that for a 90-day compressive strength of 5,000 psi, a 3-inch MSA would require less cement per cubic yard than a 6-inch MSA. Therefore, the selection of a MSA should be based on the size that will minimize the cement requirement. Another consideration in the selection of the MSA is the availability of the larger sizes and the cost of handling additional sizes. However, if the various sizes are available, the savings in cement and the savings in temperature control measures needed to control heat generation should offset the cost of handling the additional aggregate sizes.

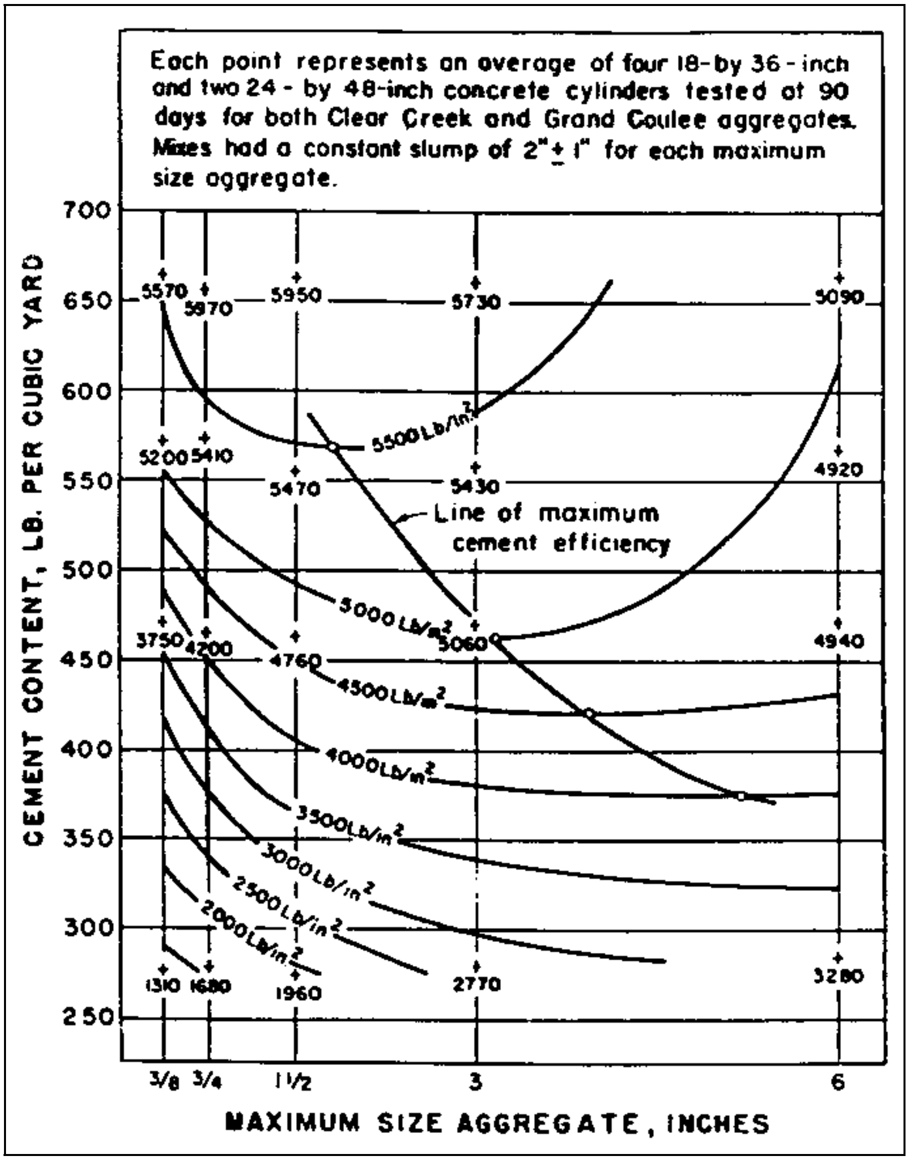

Figure 9-1. Variation of cement content with maximum size aggregate for various compressive strengths. Chart shows that compressive strength varies inversely with maximum size aggregate for minimum cement content (USBR 1981)

d. Design Age. The design age for mass concrete is usually set between 90 days and 1 year. This is done to limit the cement necessary to obtain the desired strength. However, there are early-age strength requirements that must also be considered: form removal, resetting of subsequent forms, lift line preparation, construction loading, and impoundment of reservoir. There are also some difficulties that must be considered when selecting a very long design age. These include: the time required to develop the mixture proportions and perform the necessary property testing and the quality assurance evaluation of the mixture proportions during construction.

(1) During the design phase, selection of a 1-year design strength would normally require a minimum of 2 years to complete the mix design studies and then perform the necessary testing for structural properties. This assumes that all the material investigations discussed earlier in this manual and in EM 1110-2-2000 have been completed and that the laboratory has an adequate supply of representative material to do all required testing. In many cases, there may not be sufficient time to perform these functions in sequence, thus they must be done concurrently with adjustments made at the conclusion of the testing.

(2) During the construction phase of the project, the problems with extended design ages become even more serious. The quality assurance program requires that the contracting officer be responsible for assuring that the strength requirements of the project are met. With a Government-furnished mix design, the Contracting Officer must perform strength testing to assure the adequacy of the mixture proportions and make adjustments in the mix proportions when necessary. The problem with identifying variability of concrete batches with extended design ages of up to 1 year are obvious. As a result, the laboratory should develop a relationship between accelerated tests and standard cured specimens. EM 1110-2-2000 requires that, during construction, two specimens be tested in accordance with the accelerated test procedures, one specimen be tested at an information age, and two specimens be tested at the design age. The single-information-age specimen should coincide with form stripping or form resetting schedules. For mass concrete construction where the design age usually exceeds 90 days, it is recommended that an additional information-age specimen be tested at 28 days.

9-4. Testing During Design. During the design phase of the project, test information is needed to adequately define the expected properties of the concrete. For the purposes of this manual, the type of tests required are divided into two categories: structural properties testing and thermal properties testing. The number of tests and age at which they should be performed will vary depending on the type of analyses to be performed. However, Table 9-2 should be used in developing the overall testing program. If several mixes are to be investigated by the laboratory for possible use, then the primary mix should be tested in accordance with Table 9-2 and sufficient isolated tests performed on the secondary mixes to allow for comparisons to the primary mix results. ACI STP 169B (1978) and Neville (1981) provide additional information following tests and their significance.

a. Structural Properties Testing.

(1) Compressive Strength. Compressive strength testing at various ages will be available from the mix design studies. However, additional companion compressive tests at various ages may be required for correlation to other properties, such as tensile strength, shear strength, modulus of elasticity, Poisson’s ratio, and dynamic compressive strength. Most of the compression testing will be in accordance with CRD-C 14 (USAEWES 1949), which is a uniaxial test. However, if the stress analysis is to consider a biaxial stress state, then additional biaxial testing may need to be performed.

TABLE 9-2

Recommended Testing Program

Test	1	3	7	28	90	180	1 yr.
	Age of Specimens (days)						
Compression test	*	*	*	*	*	*	*
Modulus of rupture	*	*	*	*	*	*	*
Splitting tensile test				*			*
Shear test				*			*
Modulus of elasticity	*	*	*	*	*	*	*
Poisson's ratio	*	*	*	*	*	*	*
Dynamic tests							*
Creep	*	*	*	*	*	*	*
Strain capacity		*	*	*			*
Coefficient of thermal expansion	*	*	*	*			*
Specific heat	*	*	*	*			*
Thermal diffusivity	*	*	*	*			*

(2) Tensile Strength. The limiting factor in the design and analysis of arch dams will usually be the tensile strength of the concrete. Currently there are three accepted methods of obtaining the concrete tensile strength: direct tension test; the splitting tension test; and the modulus of rupture test. The direct tension test can give the truest indication of the tensile strength but is highly susceptible to problems in handling, sample preparation, surface cracking due to drying, and testing technique; therefore, it can often give erratic results. The splitting tension test also provides a good indication of the true tensile strength of the concrete and it has the advantage of being the easiest tension test to perform. In addition, the splitting tensile test compensates for any surface cracking and gives consistent and repeatable test results. However, when using the splitting tension test results as a criteria for determining the acceptability of a design, the designer should be aware that these results represent nonlinear performance that is normally being compared to a tensile stress computed from a linear analysis. The modulus of rupture test gives a value that is calculated based on assumed linear elastic behavior of the concrete. It gives consistent results and has the advantage of also being more consistent with the assumption of linear elastic behavior used in the design. A more detailed discussion of the importance of these tests in the evaluation of concrete dams is presented the ACI Journal (Raphael 1984). In testing for tensile strength for arch dam projects, the testing should include a combination of splitting tension tests (CRD-C 77) and modulus of rupture tests (CRD-C 16) (USAEWES 1949).

(3) Shear Strength. The shear strength of concrete results from a combination of internal friction (which varies with the normal compressive stress) and cohesive strength (zero normal load shear strength). Companion series of shear strength tests should be conducted at several different normal stress values covering the range of normal stresses to be expected in the dam. These values should be used to obtain a curve of shear strength versus normal stress. Shear strength is determined in accordance with CRD-C 90 (USAEWES 1949).

(4) Modulus of Elasticity. When load is applied to concrete it will deform. The amount of deformation will depend upon the magnitude of the load, the rate of loading, and the total time of loading. In the analysis of arch dams, three types of deformations must be considered: instantaneous modulus of elasticity; sustained modulus of elasticity; and dynamic modulus of elasticity. Dynamic modulus of elasticity will be discussed in a separate section.

(a) The instantaneous modulus of elasticity is the static modulus of elasticity, as determined by CRD-C 19 (USAEWES 1949). The modulus of elasticity in tension is usually assumed to be equal to that in compression. Therefore, no separate modulus testing in tension is required. Typical values for instantaneous (static) modulus of elasticity will range from 3.5×10^6 psi to 5.5×10^6 psi at 28 days and from 4.3×10^6 psi to 6.8×10^6 psi at 1 year.

(b) The sustained modulus of elasticity includes the effects of creep, and can be obtained directly from creep tests. This is done by dividing the sustained load on the test specimen by the total deformation. The age of the specimen at the time of loading and the total time of loading will affect the result. It is recommended that the age of a specimen at the time of loading be at least 1 year and that the total time under load also be 1 year. The sustained modulus under these conditions will typically be approximately two-thirds that of the instantaneous modulus of elasticity.

(5) Dynamic Properties. Testing for concrete dynamic properties should include compressive strength, modulus of rupture or splitting tensile strength, and modulus of elasticity. The dynamic testing can be performed at any age for information but is only required at the specified design age. The rate of loading used in the testing should reflect the actual rate with which the dam will be stressed from zero to the maximum value. This rate should be available from a preliminary dynamic analysis. If the rate of loading is not available, then several rates should be used covering a range that can be reasonably expected. For example, a range of rates that would cause failure at 20 to 150 milliseconds could be used.

(6) Poisson’s Ratio. Poisson’s ratio is defined in American Society for Testing and Materials (ASTM) E6 (ASTM 1992) as "the absolute value of the ratio of transverse strain to the corresponding axial strain below the proportional limit of the material." In simplified terms, it is the ratio of lateral strain to axial strain. Poisson’s ratio for mass concrete will typically range from 0.15 to 0.20 for static loads, and from 0.24 to 0.25 for dynamic loads.

(7) Creep. Creep is time-dependent deformation due to sustained load. Creep can also be thought of as a relaxation of stress under a constant

strain. In addition to using the creep test to determine the sustained modulus of elasticity (discussed previously), creep is extremely important in the thermal studies. However, unlike the sustained modulus of elasticity, the thermal studies need early age creep information.

(8) Strain Capacity. Analyses that are based on tensile strain capacity rather than tensile strength will require some information on strain capacity. Examples of these types of analyses include the closure temperature and NISA as discussed in Chapter 8. Strain capacity can be measured in accordance with CRD-C 71 (USAEWES 1949) or can be estimated from the results of the modulus of elasticity, modulus of rupture, and specific creep tests (Houghton 1976).

b. Thermal Properties. Understanding the thermal properties of concrete is vital in planning mass concrete construction. The basic properties involved include coefficient of thermal expansion, specific heat, thermal conductivity, and thermal diffusivity.

(1) Coefficient of Thermal Expansion. Coefficient of thermal expansion is the change in linear dimension per unit length divided by the temperature change. The coefficient of thermal expansion is influenced by both the cement paste and the aggregate. Since these materials have dissimilar thermal expansion coefficients, the coefficient for the concrete is highly dependent on the mix proportions, and since aggregate occupies a larger portion of the mix in mass concrete, the thermal expansion coefficient for mass concrete is more influenced by the aggregate. Coefficient of thermal expansion is expressed in terms of inch per inch per degree Fahrenheit (in./in./°F). In many cases, the length units are dropped and the quantities are expressed in terms of the strain value per °F. This abbreviated form is completely acceptable. Typical values for mass concrete range from 3.0 to 7.5 × 10^{-6}/°F. Testing for coefficient of thermal expansion should be in accordance with CRD-C 39 (USAEWES 1949). However, the test should be modified to account for the temperature ranges to which the concrete will be subjected, including the early-age temperatures.

(2) Specific Heat. Specific heat is the heat capacity per unit temperature. It is primarily influenced by moisture content and concrete temperature. Specific heat is typically expressed in terms of Btu/pound· degree Fahrenheit (Btu/lb-°F). Specific heat for mass concrete typically ranges from 0.20 to 0.25 Btu/lb-°F. Testing for specific heat should be in accordance with CRD-C 124 (USAEWES 1949).

(3) Thermal Conductivity. Thermal conductivity is a measure of the ability of the material to conduct heat. It is the rate at which heat is transmitted through a material of unit area and thickness when there is a unit difference in temperature between the two faces. For mass concrete, thermal conductivity is primarily influenced by aggregate type and water content, with aggregate having the larger influence. Within the normal ambient temperatures, conductivity is usually constant. Conductivity is typically expressed in terms of Btu-inch per hour-square foot-degree Fahrenheit (Btu-in./hr-ft^2-°F). Thermal conductivity for mass concrete typically ranges from 13 to 24 Btu-in./hr-ft^2-°F. It can be determined in accordance with CRD-C 44 (USAEWES 1949) or it can be calculated by the following equation:

$$k = \sigma c \rho \tag{9-2}$$

where

k = thermal conductivity
σ = thermal diffusivity
c = specific heat
ρ = density of concrete

(4) Thermal Diffusivity. Thermal diffusivity is a measure of the rate at which temperature changes can take place within the mass. As with thermal conductivity, thermal diffusivity is primarily influenced by aggregate type and water content, with aggregate having the larger influence. Within the normal ambient temperatures, diffusivity is usually constant. Diffusivity is typically expressed in terms of square feet/hour (ft^2/hr). For mass concrete, it typically ranges from 0.02 to 0.06 ft^2/hr and is measured using CRD-C 37 (USAEWES 1949).

(5) Adiabatic Temperature Rise. The adiabatic temperature rise should be determined for each mix anticipated for use in the project. The adiabatic temperature rise is determined using CRD-C 38 (USAEWES 1949).

9-5. Properties To Be Assumed Prior To Testing. During the early stages of design analysis it is not practical to perform in-depth testing. Therefore, the values shown in Tables 9-3, 9-4, and 9-5 can be used as a guide during the early design stages and as a comparison to assure that the test results fall within reasonable limits.

TABLE 9-3

Static Values (Structural)

Compressive strength (f'_c)	$\geq$ 4,000 psi
Tensile strength (f'_t)	10% of f'_c
Shear strength (ν)	
Cohesion	10% of f'_c
Coef. of internal friction	1.0 ($\phi = 45^o$)
Instantaneous modulus of elasticity (E_i)	4.5×10^6 psi
Sustained modulus of elasticity (E_s)	3.0×10^6 psi
Poisson's ratio (μ_s)	0.20
Unit weight of concrete (ρ_c)	150 pcf
Strain capacity (ε_c)	
rapid load	100×10^{-6} in/in
slow load	150×10^{-6} in/in

TABLE 9-4

Dynamic Values (Structural)

Compressive strength (f'_{cd})	130% f'_c
Tensile strength (f'_{td})	130% f'_t
Modulus of elasticity (E_D)	5.5×10^6 psi
Poisson's ratio (μ_d)	0.25

TABLE 9-5

Thermal Values

Coefficient of thermal expansion (e)	5.0×10^{-6} per ^oF
Specific heat (c)	0.22 Btu/lb-^oF
Thermal conductivity (k)	16 Btu-in./hr-ft^2-^oF
Thermal diffusivity (σ)	0.04 ft^2/hr